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# THz emissions by two-color filaments in air: Revisiting the wavelength scaling

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**Abstract:** We report impressive growths in the terahertz energies supplied by air plasmas created by two-color laser pulses whose fundamental wavelength is increased. Comprehensive 3D simulations reveal the crucial role of the two-color relative phase.

OCIS codes: (320.7110) Ultrafast nonlinear optics; (350.5400) Plasmas; (260.3090) Infrared, far.

## 1. Introduction

Producing terahertz (THz) radiation by ultrashort laser pulses has become an active field of research because of its promising applications in, e.g., spectroscopy and medical imaging [1]. Efficient THz emitters can be obtained by focusing into air a two-color femtosecond light pulse, composed of fundamental (FH) and second (SH) harmonics, in order to create a plasma channel that acts as a frequency converter [2]. Recent studies [3, 4] showed that increasing the pump wavelength enhances the THz energy. However, there is no consensus on the gain factors expected when pushing the FH wavelength,  $\lambda_0$ , from the near-IR to the mid-IR range. Clerici et al. [3] reported THz energy yields scaling like  $\lambda_0^{4.6}$  in the range 0.8 - 1.8  $\mu\text{m}$ . By contrast, according to the local-current model [2, 4], the largest THz energy attained by two colors with  $\pi/2$  relative phase should follow a scaling in  $\lambda_0^2$  only.

## 2. Experimental campaigns vs numerical simulations

Here we address this apparent contradiction by performing two distinct experiments scanning the wavelength range 1.2 - 2.6  $\mu\text{m}$ . The experimental campaigns used two different OPA systems (TOPAS). Figure 1(a) summarizes the THz signals recorded with a pyroelectric detector. Despite the different wavelength ranges investigated, the fitting curves of this figure underline impressive growths in  $\lambda_0^\alpha$  with powers  $\alpha$  not only exceeding  $\sim 4.6$  [3], but also reaching up to almost 15 in the highest wavelength ranges. We also observe a decrease in the pyroelectric signal beyond specific  $\lambda_0$  values, which may indicate some optimum wavelengths where maximum THz generation is achieved. Such a behavior is present in the data points of Ref. [3] as well, recalled by the gray symbols and line.

We show that such impressive growths can be explained by changes in the laser parameters as the FH wavelength is increased [5]. Comprehensive 3D simulations combining both computations of the SH/FH energy ratio from the doubling crystal and a unidirectional numerical solver [6] are performed using the experimental values of the beam diameters and pulse durations. They reproduce reasonably well the behaviors of THz energies reported from the experiments, that is, not only a global growth in  $\sim \lambda_0^\alpha$ , but also the occurrence of optimum FH wavelengths beyond which efficiency in THz generation drops [Fig. 1(b)]. We demonstrate that the latter effect strongly depends on the phase angle between the two colors exiting the crystal, which varies with  $\lambda_0$  for a fixed distance separating the plasma zone from the doubling crystal. In particular, drops in the THz signal around specific wavelengths ( $\lambda_0 = 1.4$  and  $2.0 \mu\text{m}$ ) are due to variations in the relative phase. A constant phase angle of  $\pi/2$  at the crystal exit renders the THz energy increase monotonous (blue curve).

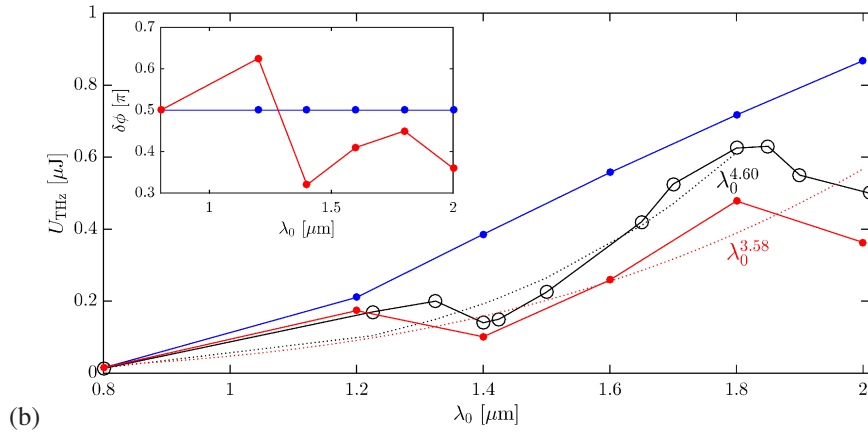
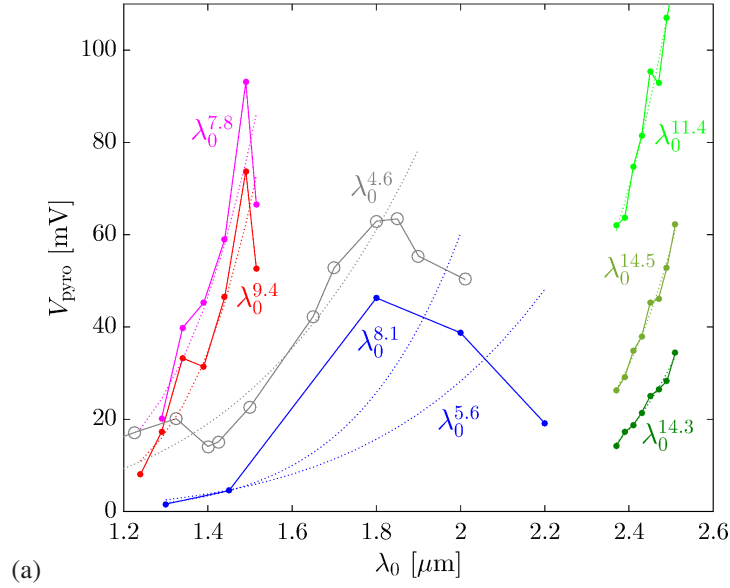


Fig. 1. (a) Pyroelectric detector signals vs FH wavelength in the frequency window  $\nu < 20$  THz for the two experimental campaigns. The average input power of the pump beam is constant for each curve, namely, 720-840 mW (red/pink curves), 300 mW (blue curve), 348-420-558 mW (green curves). Dotted curves are fitting curves in  $\lambda^\alpha$ . Gray circles recall the data of Ref. [3]. (b) THz energy yield computed with the 3D UPPE model (red dots) for the experimental data of [3] (black circles) with the initial phase shifts specified in inset. The blue curve is associated to  $\pi/2$  phase angle at the exit of the doubling crystal.

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